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PROBLEMS ASSOCIATED WITH THE STUDY OF CORAL REEFS[1]

BY PROFESSOR W. M. DAVIS
HARVARD UNIVERSITY

The Visible Features of Coral Reefs.—One of the most striking features of coral reefs is their incapacity to reveal the conditions of their origin. True, the observer on a reef, whether he is a zoologist or not, may see the extraordinary luxuriance of coral growth, and may discover that the heavier forms grow under the surf on the outer slope, while the more delicately branching forms frequent the quieter waters of the lagoon. The variety of pattern and the delicacy of coloring, as seen in the clear and quiet lagoon waters, are endlessly entertaining; but it is exceptional for them to be laid bare at low tide over broad surfaces, as they are in the Great Barrier reef of Australia, so wonderfully pictured in Saville Kent's notable volume. Hence unless the traveller is fore-

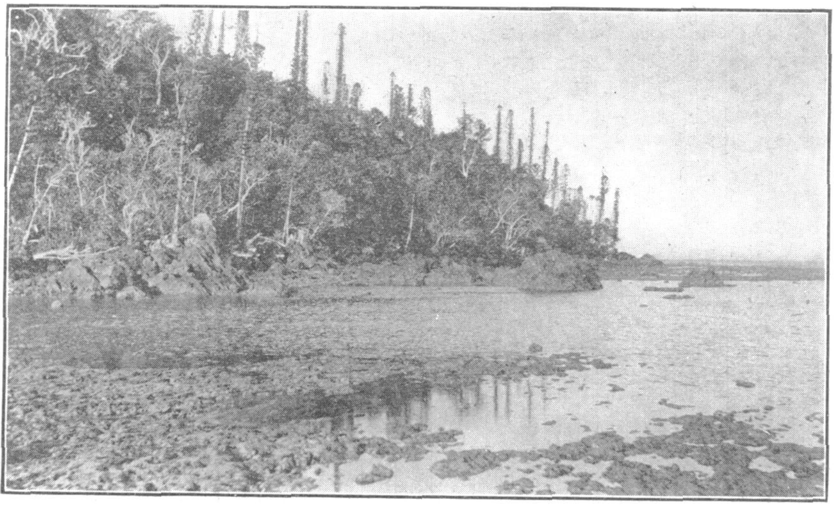

FIG. 1. FRINGING REEF, SOUTHEAST END OF NEW CALEDONIA; LOW TIDE. This is the inner part of the reef flat shown in Fig. 2. The slender trees on the headland are the New Caledonian araucaria, or pine.

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[1] Presented at the Washington meeting of the National Academy of Sciences, April 20, 1915.

warned he will be disappointed in the dull gray coral rock that prevails over the greater part of the reef flat, Figs. 1 and 2, strewn with scraps of dead coral, and holding living forms only in its little pools—occasional small corals, large dark-blue starfish, sea urchins with a small number of heavy brown spines or with a larger number of long hat-pin-like black spines, giant clams with many colored mantles lining their slightly open valves, and various kinds of calcareous algæ. He will often see large masses of coral, sometimes ten or fifteen feet in diameter, that have been torn by waves, Fig 2, from the outer face of the reef, now scattered over the reef flat, suffering slow disintegration as they are battered by later storms and shifted across the flat toward the lagoon; and in the lagoon he will find patches of growing corals surrounded by white coral sand or gray silt that is swept from the reef flat.

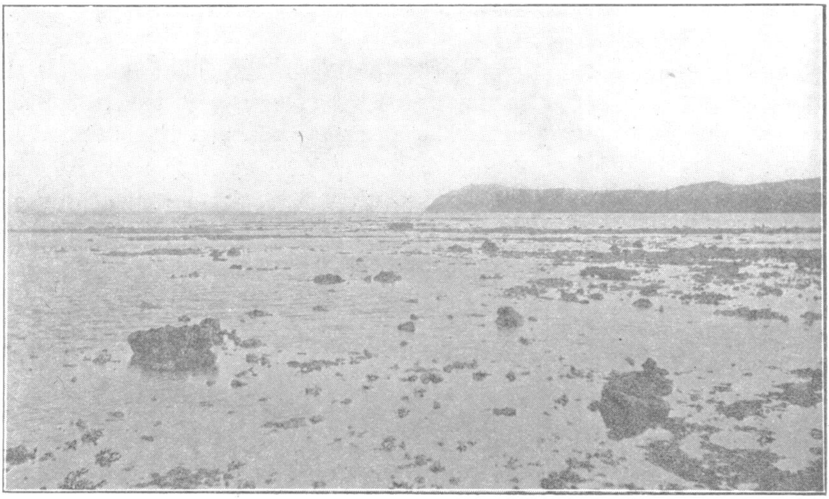

FIG. 2. REEF FLAT, SOUTHEAST END OF NEW CALEDONIA; LOW TIDE.

If he be a zoologist, he will revel in the opportunity of study in so superb a natural aquarium; he can there find the coral larvæ to be free-floating forms of pin-head size that are carried far and wide by ocean currents—some of them to add to the population of existing reefs, most of them to die in deep water, and a few to arrive by lucky chance on a reef-free coast, where they may establish themselves, if the temperature be high enough, and in time form a new reef close along the shore, known as a fringing reef. With wider experience, supplemented by sounding and dredging, the observer will learn that reef-building corals do not grow in turbid water, or at greater depths than 20 or 30 fathoms, or in latitudes where the winter temperature of the water is lower than 20° C. He may by wandering on many reefs gain acquaintance with their various forms—fringing reefs, close along shore, as already mentioned; barrier or encircling reefs, Figs. 3 and 4, separated from their mountainous central island by a shallow lagoon half a mile or several miles in width; or atolls, precisely like barrier reefs, except that their lagoon has no central island; and he may, by imagination, gain appre-

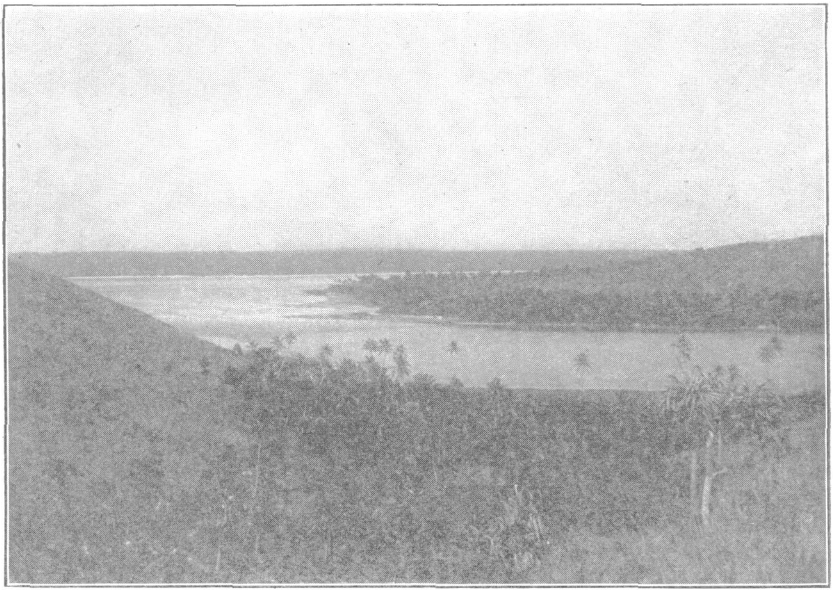

FIG. 3. BARRIER REEF, NARROW LAGOON, AND EMBAYMENT, NORTH SIDE OF NGAU, FIJI. In the mid-foreground a branch valley descends to a small delta on the side of the main-valley embayment.

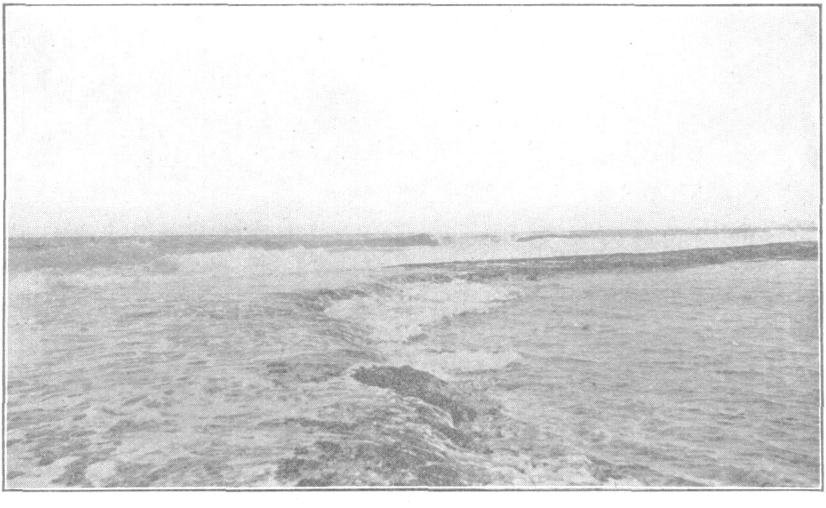

FIG. 4. SURF ON THE BARRIER REEF OF RAIATEA, SOCIETY ISLANDS; HALF TIDE.

ciation of the secondary and larger meaning of the term, coral reef; for, as employed by Darwin, Jukes, and others, it means not only the visible structure at sea level, but also the whole calcareous undermass that has been added in bench-like form around its foundation; of small volume in narrow fringing reefs, probably of enormous volume in large atolls.

During these entertaining wanderings and reflections the observer may consciously, yes, insistently, review the various theories by which the origin of coral reefs has been explained. But so long as he confines his attention to the sea-level reefs, he will not be able to make sure which one of the eight or nine competing theories is the right one: for sea-level coral reefs reveal only their existence in the present, not their origin in the past. Apart from indications as to limiting depths and temperatures, as just stated, the visible reefs give no conclusive testimony as to the conditions and processes of their past formation. It is probably for this reason that so many contradictory, mutually irreconcilable hypotheses concerning the mode of reef formation have been invented. There was, to be sure, a period from 1840 to 1870 when Darwin's theory of upgrowth during intermittent subsidence, gained universal acceptance; for it completely superseded a few earlier theories and for a long time had no competitors. But after undisputed success for a generation, several rival hypotheses were brought forward, and then for some thirty years the universal agreement previously prevailing was succeeded by many and wide differences of opinion. The truth of the matter is that, during this period, the coral-reef problem has been encumbered by the rivalry of several immature, imperfectly argued, and really incompetent hypotheses, whereby progress has been embarrassed if not hindered. But during the past thirteen years several Australasian students of coral reefs in the Pacific, and for a shorter period a few students in the Atlantic, have been finding evidence that has led them to set aside the newer unsatisfactory views and return to or towards Darwin's theory. Such was the condition of things, when, aided by a liberal grant from the Shaler Memorial Fund of Harvard University and by a generous subsidy from the British Association for the Advancement of Science, which carried with it an invitation to attend the colonial meeting in Australia, I was enabled to spend the greater part of the year 1914 in visiting a number of reef-encircled islands in the Pacific ocean, for the purpose of examining on the ground as carefully as possible the merits of the various theories that have been brought forward in explanation of these extraordinary structures.

Theories of Coral Reefs.—Before starting on this journey, I made a preparatory review of the rival hypotheses,[2] in which I was aided by several references supplied by Dr. T. W. Vaughan, of Washington, whose studies of Atlantic reefs began some years before mine were undertaken on the Pacific. In this review especial attention was given to the critical tests by which the success of the several theories could be measured, and the review confirmed me in the belief that Darwin's original theory, invented, as he tells us, before he had ever seen a true coral reef, is by far the most successful of all. I say "confirmed in the belief," because earlier still, I had prepared a diagram to set forth the special merits of Darwin's theory, as they were then understood: indeed twelve years ago my opinion favoring Darwin's views was briefly stated in a small text-book; but, it is regrettable to add, such was the weight of authoritative counter statements that my belief in Darwin's theory was for a time weakened; yet it was soon strengthened again when making the preparatory review over a year ago. This must be made plain, so that any one may estimate for himself whether, in what is now to follow, my presentation of the case is prejudiced, and particularly whether I am guilty of that grievous error known as "special pleading"—arguing in favor of some favorite theory—instead of giving impartial consideration to all. My preference would be to make an impersonal, objective presentation of the problem; but inasmuch as a number of different theories must be examined, some attention must be given to the experience, the qualifications and the methods of their inventors; thus the discussion inevitably becomes somewhat personal. One of the most interesting results of the preliminary inquiry of a year ago was that an investigation of the coral-reef problem inevitably leads far away from the direct study of corals and coral reefs, and enters upon the discussion of many other problems which at first might seem to have no relation to it: it is for that reason I have entitled this address: "Problems associated with the Study of Coral Reefs."

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[2] The Home Study of Coral Reefs, *Bull. Amer. Geogr. Soc.*, XLVI., 1914, 561–577, 641–654, 721–739.

Methods of Investigation.—Now if coral reefs themselves are so uncommunicative as to their past history, the search for their origin—whether they are fringing reefs, close alongside of an island or a continental shoreline, or barrier reefs, separated from the shore by a shallow lagoon, or atolls standing alone in the ocean—can not be successfully prosecuted until the fundamental problem of how to conduct a scientific investigation of this kind has been duly considered. Let me therefore state briefly that the method of investigation which is here selected—it is more fully set forth in the preparatory review above referred to—demands, first, the observation of pertinent facts and the review of published observations by others: then, spurred on by the spirit of wondering inquiry and aided by related knowledge, it appeals to speculation, imagination and invention, or borrows from the speculation, imagination and invention of others, in the hope of thus coming upon the mental concepts or "hypotheses" of all the possible ways in which reefs could ever have been formed; and when this has been done the investigator arrives at the ponderous question: Which one of all these hypotheses is right? He might at first answer this question by saying: Visit the reefs themselves with the various theories in mind, and see which one best accounts for the facts there observable; but if this advice is literally followed, no satisfactory result is obtained from it, for the reefs are so complacently indifferent that they make no objection to any one of the eight or nine theories that have been proposed to account for them. Of course they make no objection, for no theory would get so far as being announced if it did not at least explain the visible facts of the reefs that it was invented to explain! A really successful theory must do much more than that: it must, in Chamberlin's phrase, explain various things that it was not invented to explain; for example, facts that were not thought to be connected with reefs, or facts that were not known when it was invented.

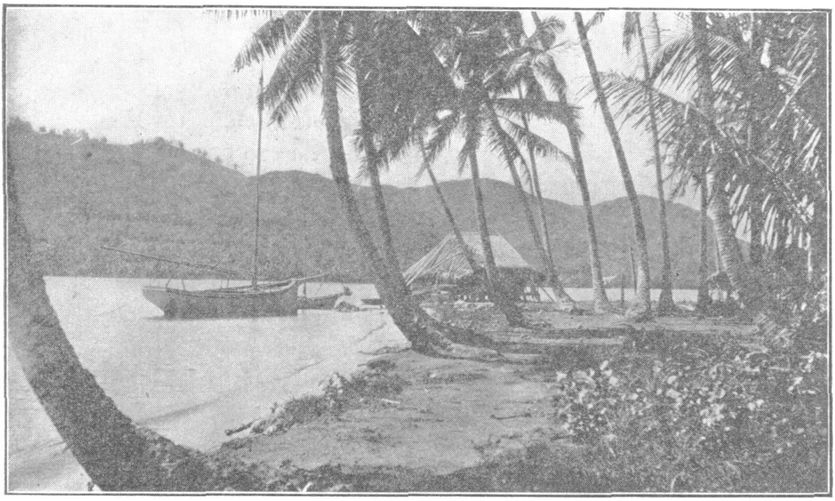

FIG. 5. ACROSS FAAROA BAY, EAST SIDE OF RAIATEA, SOCIETY ISLANDS.

In order to see if a theory can stand this added test, its consequences must be logically deduced from the postulated premises and impartially confronted with the the appropriate facts. Confrontation as well as deduction demand concentration of attention on the problem in hand, and the exclusion as far as possible of all distractions, such as the remote and picturesque reef-encircled islands afford in abundance. If the confrontation is successful, the theory is good; if unsuccessful, the theory is erroneous. But why should a truism like this be stated in these modern years! Because, surprisingly enough, a review of the published studies of the coral-reef problem leads to the conclusion that, with a few distinguished exceptions and those chiefly in the works of Darwin and Dana or their followers, the methods employed have been incomplete, illogical and untrustworthy, and the results reached are therefore unconvincing.

Outgrowing Reefs on Still-standing Islands.—For example, several observers thirty-five or forty years ago came to believe that reefs are formed by outgrowth on their advancing talus around still-standing foundations. One of these observers was a zoologist of limited experience with coral reefs in the Atlantic; another, also a zoologist, had a more extended experience with coral reefs in the Pacific, but seems to have been little informed in physical geology; a third was a distinguished explorer of the oceans, who early in his scientific career came independently on this still-stand theory, as it may be called, which has become known chiefly through his vigorous advocacy of it. In an article which gave more attention to another scheme, here considered on a later page under the name of the "up- and outgrowth theory," he briefly stated his simpler theory substantially as follows:

The still-stand theory supposes that coral reefs, once established by colonizing larvæ as fringing reefs on a suitable foundation such as the shore of a young volcanic island, have been enlarged by outward growth on the advancing talus of their own detritus, the still-standing island suffering no change in attitude with respect to sea level while it is slowly worn down lower and lower as the reef grows outward; at the same time the inner part of the reef is dissolved away and converted into a shallow lagoon, so that the initial fringing reef is in time developed into a barrier reef. Finally the central island may be completely worn away, leaving an uninterrupted central lagoon, so that the barrier reef becomes an atoll. The "distinguishing feature" of this theory, as described by its inventor, is that, in conjunction with the associated theory of up- and outgrowth, by which atolls may be built up on submarine volcanoes crowned with an "organic rain" of calcareous deposits here to be discussed later, it does away with "the great and general subsidences" involved in Darwin's theory. He concluded:

> If it has been shown that atoll and barrier reefs can be formed without subsidence, then it is most unlikely that their presence in any way indicates regions of the earth's surface where there have been wide, general and slow depressions.

But why should one possibility exclude another! It is apparently true, as an abstract proposition, that coral reefs may be formed by outgrowth around still-standing islands, as this oceanographer had suggested; but a geologist asks not merely by what processes coral reefs may have been formed, but how they really have been formed. Yet because coral reefs may have been formed in a certain way, the scientific world was urged to believe that they have been formed in that way; indeed, the third inventor of this still-stand theory later rejected the possibility of reefs being formed by upgrowth during subsidence, and regarded his possible scheme of outgrowth on a still-standing foundation as the equivalent of actual processes, for he eventually said:

> It seems impossible with our present knowledge to admit that atolls or barrier reefs have ever been developed after the manner indicated by Mr. Darwin's simple and beautiful theory of coral reefs.

Consequences of the Still-stand Theory.—What procedure should be followed with respect to the still-stand hypothesis by an unprejudiced inquirer? Evidently he should ask: What are all the deducible consequences of the hypothesis; which ones of these consequences can be confronted with the observable facts of to-day; and particularly which ones of the confrontable consequences are unlike the corresponding confrontable consequences of competing hypotheses. These steps are indispensable in any well ordered investigation into the past origin of existing features; and they are particularly desirable here, because they were almost wholly neglected in the statement of the theory by its leading advocate. For example, so important an element of the theory as the wearing away of the central island was very briefly treated, chiefly in a single sentence:

> In the case of the atoll the cone may have been reduced below the level of the sea by the waves and atmospheric influences.

So summary a disposition of the matter is insufficient. The successive stages of this long process must be reasoned out; otherwise the theory can not be thoroughly tested. The successive stages of change must, indeed, be reasoned out with equal care and fairness for every alternative scheme, for only thereby can the investigator guard himself against becoming unwarrantably fond of some special hypothesis. He must make an effort consciously to deduce all the consequences of each hypothesis, lest an important consequence remain overlooked. He must then select those consequences which may correspond to existing facts; the others can not be used in testing the hypothesis from which they follow. And he must give special attention to those consequences of each hypothesis which contradict corresponding consequences of the rival hypotheses, because it is only in this way that crucial tests can be found which select a certain hypothesis as the successful one, and point out the others as incompetent. There is nothing whatever new about all this; the only surprising thing is that the method has not been consistently applied instead of, as a rule, unconsciously neglected in coral-reef studies.

It has been noted above that, in following the procedure thus indicated, we must often turn from coral reefs and consider various associated problems. In the case before us, we must consider the changes that a still-standing oceanic island will, while the reef is growing outward around it, suffer under the attack of subaerial erosional forces which wear its initial form down lower and lower as the reef grows larger and larger and the lagoon becomes wider and wider, till after the island reaches the form of a penultimate lowland, it is consumed by the waves

—not however by the heavy waves of the deep and open ocean, but by the moderate waves of the shallow and enclosed lagoon. To illustrate this we may assume that a young volcanic island of simple conical form and roughly circular rim is built up by eruption from the ocean bottom, and that a narrow fringing reef is established on its shore, as in sector *G* on the left side of Fig. 6. As the reef grows outward, sector *H,* on its advancing talus and a lagoon is more or less completely dissolved out behind it, the bottom of the lagoon should consist of ragged, dissolving limestone, or of insoluble residue. At the same time the central island suffers erosion; radiating valleys are excavated in its slopes and deltas are formed in the shallow lagoon, or on the inner part of the reef if it be not already dissolved away. Reefs thus formed should tend to become broad and continuous, with marks of outward growth in the form of prograded beach ridges; islands of coral sands should be built by the waves on the reef flats and soon become covered with vegetation. The process continues, as in sector *J,* where the volcano is much reduced in altitude while the deltas have been built forward to greater size and have become laterally confluent; and later in sector *K,* where the island is reduced to a lowland surrounded by a broad alluvial plain just above sea level; the structure of the reef is here shown in a vertical section *M,* on the side of sector *K;* the submarine talus layers must slant into deeper and deeper water at a steeper angle than the slope of the volcanic cone, the buried surface of which is not eroded, for by the conditions of the hypothesis that part of the cone has never been above sea level to suffer the attack of eroding agencies. At last in sector *L,* the lagoon waters are supposed, in a manner not clearly stated in the original account of this hypothesis, to have removed not only the alluvial delta plain but the central volcanic lowland also, except perhaps for some low residual hills; when they vanish the reef must be called an atoll; not that the

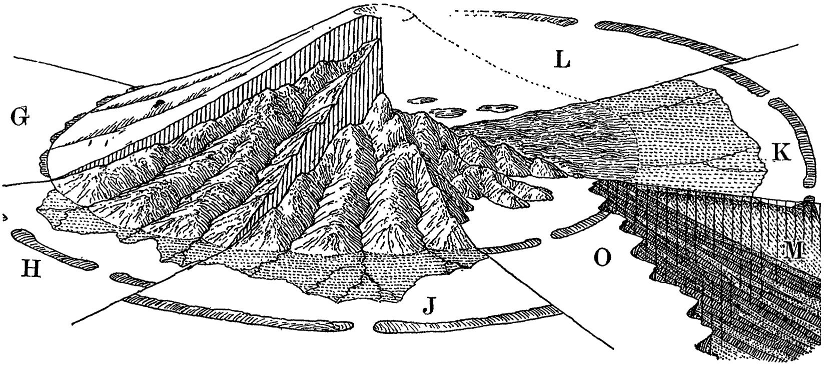

Fig. 6. Diagram of Successive Stages of Reef Formation, as deduced from the theory of outgrowing reefs on still-standing islands: sector *O,* type of actual barrier reef and its embayed central island.

reef itself has in any way changed its nature, but that the lagoon is then uninterrupted with a depth of 10, 20 or 30 fathoms.

Confrontation of Still-Stand Consequences with Facts.—Now this is all, with the possible exception of the excavation of the atoll lagoon 20 or more fathoms deep across the volcanic lowland, easily conceivable; it may have happened, but how can we tell if it really has happened; how can we know that the hypothetical scheme, here represented graphically, truly corresponds to the history of any actual coral reefs? Only by confronting the deduced consequences of the hypothesis with the appropriate facts of observation. There is absolutely no other logical method of procedure in the coral-reef problem or in any similar problem. Where then shall we look for the appropriate facts with which the deduced consequences are to be confronted? First, in young, little dissected volcanic islands around which discontinuous fringing reefs form a narrow and incomplete girdle. Such islands are occasionally found, and thus give observational warrant for the initial conditions postulated in the still-stand hypothesis: but, as the same initial conditions are postulated in certain other hypotheses, no critical test for the correctness of the still-stand hypothesis is thus secured. We must look next at sea-level reefs of the barrier or atoll class: they confirm the possible correctness of the hypothesis, because the deduced features of barrier and atoll reefs are essentially the same as the visible features of the actual reefs—of course they are, for these sea-level reefs are the very facts which the still-stand hypothesis was invented to explain; and, if it had not explained them, it would never have been published. But the difficulty here is, that all the other hypotheses do exactly as well: they also explain the barrier and atoll reefs that they were made to explain; hence no crucial test is yet provided by means of which a choice among the competing hypotheses may be made.

What do the observable features of a lagoon within a barrier reef or atoll say, when the expected features of a lagoon as deduced from the still-stand hypothesis are confronted with them? As far as actual lagoons have been studied they contradict the idea of excavation by solution or otherwise, for they seem to be the seat of sedimentation; the sediments being supplied either by calcareous overwash from the reef, by organic deposits formed within the lagoon itself, or by outwash from the island streams. But it is to the form of the central island within a barrier reef, or to the internal structure of an elevated reef that we must give special attention, for there the consequences deduced from the hypothesis include several details that had not been observed or thought of when the hypothesis was invented; and it is the unforeseen consequences of a theory that are of special importance in testing its value. Of these two witnesses, the central island gives the most outspoken and unimpeachable testimony. Hence to the central islands of barrier reefs we will for the moment attend.

The Central Islands of Barrier Reefs.—The question now before us is: Are the features of an imagined central island, as deduced from the hypothesis here under consideration, successful counterparts of actual central islands? No, they are decidedly unsuccessful. The central islands of various barrier reefs, such as Ka-ndá-vu, Fig. 23, in the Fiji group —one of the thirty or more reef-encircled islands that I saw in 1914 in the Pacific—and various other central islands that were then seen or that have been studied before and since on large-scale charts, contradict the deduced features of the hypothetical still-standing islands in certain essential particulars. A common type of actual island is shown in sector *O*, of Fig. 6; its base line is not simple, as in sectors *G* to *K*, but elaborately embayed; and the large confluent deltas that should advance outside the simple margin of a well-dissected island, as in sector *J*, are represented only by small, separate deltas at the heads of bays and coves. Darwin long ago recognized that, in the embayed island of Vanikoro, which sector *O* represents sufficiently well, "the unusual depth of the channel [lagoon] between the shore and the reef . . . and the small quantity of low alluvial land at the foot of the mountains, all seem to show that this island has not remained long at its present level." Furthermore, inasmuch as the Pacific contains many barrier-reef islands and many more atolls, we ought, if the hypothesis under consideration be correct, to find also a good number of worn-down islands in the intermediate stage of sector *K*; but not a single example of such an island has been discovered. Again, the almost-atoll stage of sector *L* shows the small residual volcanic hills to be of low and subdued form; yet the actual form of residual volcanic hills which occupy only a small fraction of their lagoon, resembles the summits of the dissected volcano shown in sector *O*. Finally, not a single example of many elevated reefs and atolls has been described as consisting wholly of the slanting talus structure demanded by this hypothesis, as shown in section at *M*, Fig. 6. Hence, although the hypothesis explains the facts regarding the sea-level reefs that it was made to explain, it fails to explain certain other equally essential facts, and it must therefore be rejected.

What commended the Still-Stand Theory?—Thus we are led back to the conclusion that Darwin reached long ago, for in his book on "Coral Reefs," published in 1842, he considered the possibility of outgrowing reefs around still-standing islands, and, as the quotation given above shows, wisely rejected it, because the consequences to which it led were not supported by the facts. Yet in the recent history of the coral-reef problem this crude hypothesis, instead of being rejected by every one, has been cordially received by a number of eminent geologists. What can have commended it? Did its chief advocate carefully discuss various alternative hypotheses and show them to be insufficient? He may have done so privately, but he published no such discussion. Did he discuss his own theory by analyzing the associated problems and deducing their consequences in systematic fashion, in order to confront the consequences with the facts and thus reach an impartial judgment? It is of course possible that he may have done so, but his published articles do not suggest that he did. Is the fundamental postulate of a still-standing island a sound one? No, for practically every oceanic island of which the history has been worked out in detail is found to have suffered some sort of change of attitude with respect to sea-level: hence the postulate of a still-standing island is probably incorrect. Can it be, perhaps, that the advocate of the still-standing hypothesis was so fully experienced in the study of coral reefs and of volcanic islands that his opinions were thereby well recommended? If we judge by the favorable consideration that has been so widely given to his hypothesis, this would appear to be the case; but alas, it was not. The advocate had been, before announcing the hypothesis, a member of an exploring expedition, which had truly enough visited several volcanic and coral islands in the Pacific and the Atlantic, but the official narrative of the expedition states that the study of coral reefs was not within its scope; hence we must suppose that the coral-reef problem was not closely attended to during the voyage.

Neglect of Essential Factors.—Nor could the literature of the coral-reef problem have been closely examined by the advocate of the still-stand theory either before or after the voyage, although the scientific world has a right to expect that it should be so examined by anyone who, discarding a generally accepted theory, proposes to replace it by a new hypothesis. Had such an examination been made, an important factor of the problem—Dana's principle of shore-line development—would have been found, clearly announced by a competent investigator and published thirty years earlier; and this factor would have prevented the acceptance of the new theory and reestablished confidence in the older theory. Indeed, if this factor had not been overlooked, the embayments of certain Pacific islands would probably have been correctly instead of incorrectly interpreted by the advocate of the still-stand theory; and he would thereby have been saved from presenting, in the report of the expedition to which he was attached, an erroneous account of the maturely dissected, reef-encircled volcanic island of Matuku, in the Fiji group, where a drowned-valley embayment on its western side is described as a crater. Had the neighboring ring-shaped volcanic island of Totoya been visited, instead of Matuku, a crater, or rather a huge caldera, of volcanic origin would truly have been found, and such a caldera does not of itself testify against still-stand, for it may have been formed by explosion or by engulfment either below or above sea-level; but to mistake the embayment of Matuku for a crater is very much as if a traveller unacquainted with the effects of tornadoes on village architecture should, on following a storm track to a ruined dwelling house, mistake its dilapidated cellar, half-filled with rain water, for its vanished attic. The chief embayment of Matuku is, like the many smaller ones, really a valley of erosion, deeply carved below any crater that may once have existed aloft, now half drowned by subsidence and therefore occupied by sea water. Three summits rise over 1,200 feet above the bay, about two miles distant on the northeast, east, and southeast; a sounding, about as far to the west of the bay as the three summits stand on the other side, shows a depth of 400 fathoms; two miles farther west the depth is 975 fathoms.

A few pages farther on the report of the same exploring expedition announces a recent and slight elevation of a few feet in the wonderfully embayed Fiji island of Ka-ndá-vu, but says not a word of the evidence of vastly greater previous subsidence that an island of such pattern loudly proclaims. Evidently then, the problem of the sculpture of volcanic islands and the origin of their shorelines, closely associated as it is with the problem of coral reefs, had not been solved, nay, had not even been seriously studied by the advocate of the hypothesis that barrier reefs and atolls may be formed by outgrowing corals, advancing on their own talus around still-standing islands, while the lagoon is etched out by solution and the island is worn down by erosion behind them. No wonder, therefore, that his incompetent hypothesis satisfied him.

An Exceptional Island.—Is there then nothing to be said for the still-standing scheme? Yes, the island of Tahiti in the Society group has been instanced as supporting this hypothesis, for it has salient and imperfectly confluent deltas inside of its barrier reef, as the hypothesis of a still-standing island demands; but Darwin long ago recognized that such salient deltas are exceptions on barrier-reef islands, and correctly explained them as marking, not a perpetual still-stand, but a pause in subsidence. He said: "At the Society archipelago . . . the shoalness of the lagoon channels round some of the islands, the number of islets formed on the reefs of other, and the broad belt of lowland at the foot of the mountains, indicate that, although there must have been great subsidence to have produced the barrier-reefs, there has since elapsed a long stationary period"; and he adds: "This probably is the ordinary course of events, subsidence supervening after long intervals of rest." He was right, for the heads of the projecting deltas at Tahiti, Fig. 12, commonly enter a mile or more into the radial valleys back of the spur ends, precisely as they should if the island had been somewhat depressed after it was dissected, and had stood still for a time after it was depressed.

Why Was the Still-Stand Theory Accepted?—Why, then, if the hypothesis of outgrowing reefs around still-standing islands really has so little recommendation, did it ever gain so much attention? Partly, I think, because, although very briefly announced, it was stated with confident emphasis instead of with critical analysis; for confidence and emphasis go, even in science, a great way; partly also because no mention was made of certain critical facts, namely, the embayed shorelines of the central islands with small deltas at the bay heads, which contradict certain essential consequences of the theory, namely, non-embayed shorelines with large outstanding deltas. The readers of the article which contained this "totally new departure in coral-reef literature," as an able critic wrote, seem to have accepted it as a complete statement of the case, from which no essential facts were omitted. Indeed one of the most competent of them, everywhere recognized as a leader in geological science, championed it by saying: "We are driven to admit that barrier reefs may be formed without subsidence of the sea floor." Thus the hypothesis of outgrowing reefs around still-standing islands—a hypothesis that involves the extremely improbable fundamental postulate that oceanic islands usually stand still, a hypothesis that was constructed on an inadequate basis of incomplete observation, a hypothesis that was framed without careful study of the literature of coral reefs, a hypothesis from which all consideration of an important associated problem was omitted and from which certain essential consequences could not, therefore, be critically deduced—was announced with confident emphasis and championed with authoritative recommendation; and, as a result this incompetent hypothesis has been, especially with regard to barrier-reefs, a bar to progress for thirty years; not because it was invented, but because it was announced and accepted without sufficient study of associated problems, by means of which alone its competence could be determined.

Let me here explain briefly why so much time has been given to the consideration of an incompetent hypothesis. First, because it has been accepted by many home-students of the coral-reef problem; on that ground rather than on its merits it deserves attentive consideration. Second, because it is the duty of any investigator of a problem such as we are now discussing to examine on his own responsibility every hypothesis that has been put forward to explain it; and because it is particularly his duty to search out all the points where he has to differ from others who, just as earnestly as himself, have been striving for the truth. Finally, because it is part of his task to learn if possible the grounds which led to the acceptance by others of what is to him unacceptable. Under the actual conditions of the case thirty years ago, it was perhaps not unnatural that many home-students of coral reefs should have accepted the still-stand hypothesis; for its advocate was a man of great experience in oceanographic work, of inspiring enthusiasm, and of delightful personality; and its leading champion was a man of exceptional competence in all branches of geological science and of unusual skill in the presentation of geological problems. More important still, both of these investigators frankly avowed that they had adopted the new still-stand hypothesis because it seemed more successful in explaining coral reefs than Darwin's hypothesis of subsidence which they had previously regarded as correct, but which they had come to regard as unsuccessful. Both of them were genuinely and sincerely devoted to scientific research; hence how could any one, who had not the time to investigate for himself the question at issue, hesitate to accept the conclusion of these two eminent experts!

It was therefore, as above said, not unnatural, under the conditions of the case thirty years ago, that the hypothesis thus proposed and guaranteed should go far toward replacing an earlier hypothesis that had till then enjoyed universal acceptance; but unhappily there is one condition of the case that, as already indicated, weakens it most seriously. Both the advocate and the champion of this hypothesis had omitted from their discussion a certain essential factor of the problem, namely the pattern of the central-island shoreline within barrier reefs; worse yet, they had, as above noted, completely overlooked a clear and conclusive statement regarding the pattern of the central islands of barrier reefs that had been published some thirty years before in easily accessible works by an earlier and highly regarded investigator of the coral-reef problem, who surely must have been known by name to both the advocate and the champion of the new hypothesis. Hence, natural as it was that the apparently complete statement of the still-stand hypothesis should have found wide acceptance, it must be given up when the previously omitted elements of the problem are found to speak uncompromisingly against it.

Veneering Reef on Wave-cut Platforms.—Let us now turn to another hypothesis: one which, without the intervention of a fringing reef, explains a barrier reef by supposing that it is a relatively thin veneer of coral limestone built on the outer edge of a platform that has been cut by sea waves around a still-standing volcanic island; and which explains atolls without the intervention of barrier reefs by supposing them to be veneers on completely truncated, still-standing volcanic islands. This hypothesis, like the one already considered, postulates still-standing volcanic islands; in view of the small thickness of its reefs it may be called the veneering hypothesis. Here the associated problem that we must consider is somewhat more complicated than before, because it includes the attack of the sea around the undefended island margin as well as that of subaerial erosion over its surface. A special sequence of forms must be produced as an island is worn away by the double attack, and the chief members of the sequence must be deduced, in order that they may be confronted with the facts. It is curious to note that here, as in the case of the previous theory, this duty has been altogether neglected. Under the double attack, a volcanic island, originally conical and undefended by any reef, will soon be cut away by the waves around its shore, like Nightingale island in the South Atlantic, well figured in the narrative volume of the *Challenger* Report, while rain and streams are furrowing its slopes: the wave-cut platform will be backed by a steep cliff, notched at the top by hanging valleys, as in sectors *H* or *J*, Fig. 7. If a veneering reef is now established on the platform edge, as at *H′* or *J′*, the retreat of the cliff, as a cliff, will soon cease, and the hanging valleys will be cut down to sea-level; deltas will grow in front of the valleys, and a talus will gather in the quiet water at the cliff base, which was clean swept by breaking waves before. If the veneering reef is not so soon established, the platform will be cut back to a greater width and the cliff to a greater height; this stage is verified by Tristan d'Acunha, another solitary volcanic island in the South Atlantic, also figured in the *Challenger* narrative; on such becliffed islands, cascades from hanging valleys have been described, which give warrant for the hanging valley as a deduced feature of sector *J,* Fig. 9. An undefended island may be almost consumed, as in sector *K,* when only small stacks will remain; or it may be completely truncated before a reef is established, and then the reef will form an atoll.

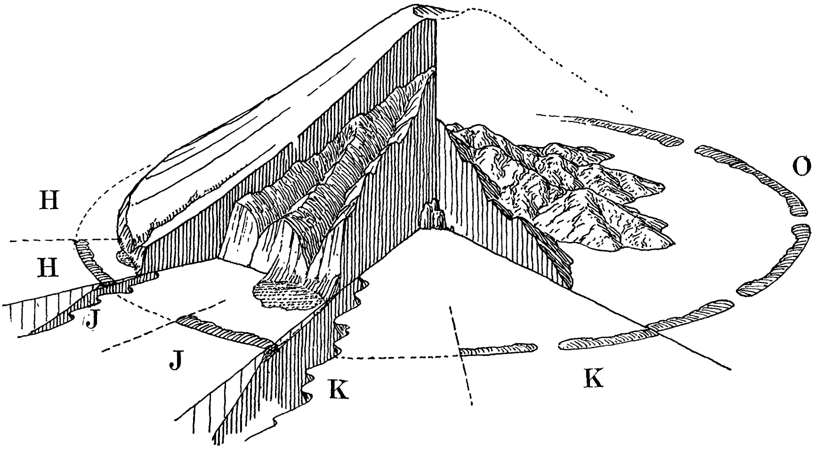

FIG. 7. DIAGRAM OF SUCCESSIVE STAGES OF REEF FORMATION, as deduced from the theory of veneering reefs on wave-cut platforms: sector *O,* type of actual barrier reef and its embayed central island.

Unsuccessful Consequences of the Veneering Theory.—Are the consequences of this theory, here graphically presented, confirmed when they are confronted with the facts of actual coral reefs and their associated islands? No, decidedly not. As before, the central islands of barrier reefs are again the most important independent witnesses put forth by the facts. Such islands are not cliffed around a non-embayed shoreline; they are, with hardly an exception, embayed between non-cliffed spurs, as in sector *O,* Fig. 7, or in Fig. 3. Furthermore, as there are many atolls in the ocean there should be also, if the veneering hypothesis were true, many almost finished atoll platforms; that is, many wave-swept platforms not yet enclosed by veneering reefs, with a becliffed island remnant rising from the center; but no such becliffed island remnants in the center of a wave-swept rock platform are known except on the borders or outside of the coral-reef zone. Again, there are no known examples of elevated reefs possessing the structure here demanded; elevated reefs are often hundreds of feet in thickness, and in no case are they reported to lie on broad wave-cut platforms. Finally, this hypothesis is defective in that it furnishes no reason for the postponement of reef establishment while the platform is suffering preliminary abrasion, or for the early establishment of a veneering reef on a narrow wave-cut platform, or for the long delay before the establishment of a reef on a broad one. As a matter of observation, fringing reefs are occasionally found on young volcanic islands around which no cliff-bordered platform has been abraded, and after such reefs are formed, the waves can no longer attack the island back of the reef and cut platforms on it.

Is the hypothesis of veneering reefs perhaps recommended by any special expertness of its advocates? No. The first observers to advocate it were two missionaries, about eighty years ago. Did they deduce the essential consequences of the hypothesis, somewhat as above, and confront them impartially with the facts? No: they left that for Darwin to do a few years later; and when he showed that the central islands of barrier reefs have no such cliffs as the hypothesis demands, it was properly enough set aside in favor of his hypothesis of intermittent subsidence. But it was revived about fifty years later, this time by a surgeon of the British navy who had spent some years on certain islands of the coral zone but who was unfortunately untrained in physical geology; and again by a hydrographer, expert in marine surveying but apparently not practised in making critical choice among competing hypotheses; and by a zoologist and oceanographer of great experience, but in his case also without careful deduction of the becliffed consequences, and without any mention of the good and sufficient reasons that led Darwin to reject the hypothesis sixty years earlier. Did these later advocates of the veneering hypothesis give reasons for rejecting other hypotheses and preferring their own? It must be supposed that they thought they did, but their reasons are not convincing.

Insufficient Consideration of Possible Alternatives.—For example, one of them said: "I will pass over the theory of subsidence, supported though it was by Dana, Couthouy and Beete Jukes, because the recent facts concerning the ocean depths and the regions of living and upraised reefs compel us to regard it as no longer necessary"; that is, of two alternatives, he rejected one because its postulated subsidence was made no longer "necessary" by the possible correctness of the other; but he did not apply any impartial and crucial test as a means of making a logical choice between the two. Again the same investigator said:

> The more gradual the land-slope, the broader will be the submarine ledge [platform] cut out in the course of ages by the action of the sea, and the more distant will be the barrier-reef, that has grown up along its margin [as in Fig. 8]. This I believe to be the true explanation of the position of barrier reefs.

Yet is it not immediately manifest that the same relation will obtain in upgrowing reefs during subsidence, as Fig. 9 shows; and is it not further manifest that if this relation is produced by subsidence, it must be associated with an embayed central island, like the unsymmetrical fault-block island of Wakaya in central Fiji, as in the foreground of Fig. 10; while if it is produced by wave-cutting it must be associated with a cliff-rimmed, but not embayed central island, Fig 8, the like of which does not exist in the coral seas! Furthermore, there are well-known examples of central islands that have symmetrical slopes, but that stand to one side—sometimes to windward—of the lagoon center; witness, as in the background of Fig. 10, the island of Makongai, not far from Wakaya, both enclosed in a figure-8 barrier reef; or the island of Mbengha, farther southwest in the Fiji group; these eccentrically placed residual islands are the natural result of the submergence of an unsymmetrical initial island, such as might have been composed of several unequal volcanoes welded into a single mass; and as they both have embayed but not becliffed shore lines, they must have been diminished by submergence, not by abrasion.

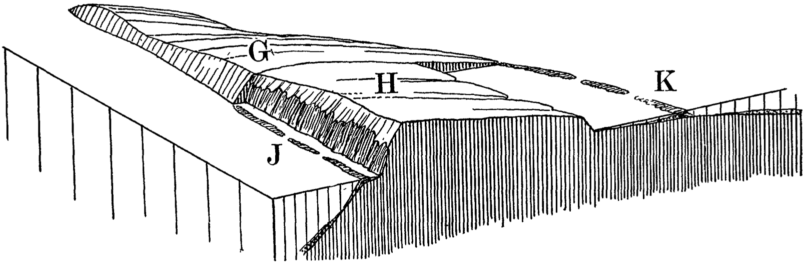

FIG. 8. DIAGRAM OF AN UNSYMMETRICAL ISLAND, *G*, on both sides of which, *H*, shallow platforms are cut by waves, and reefs, *J*, *K*, are formed.

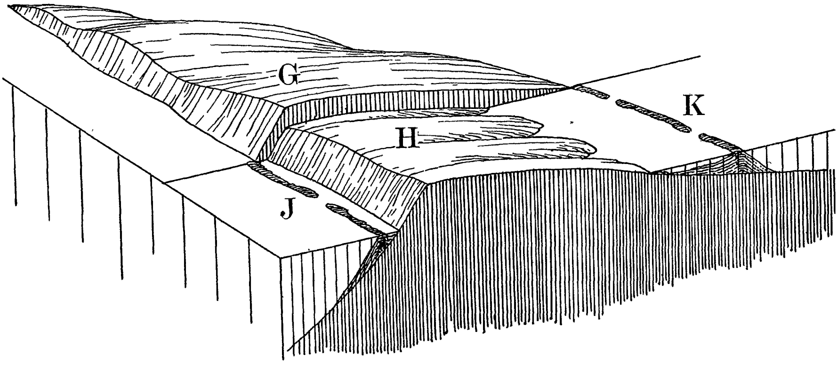

FIG. 9. DIAGRAM OF AN UNSYMMETRICAL ISLAND, *G*, which subsides, *H*, as reefs, *J*, *K*, grow upward alongside of it.

In view of such examples as these, all of which have long been charted, why should the author above quoted reject the possibility of submergence and accept the possibility of abrasion as a matter of opinion or preference, instead of submitting both possibilities to some impartial and adequate tests, such as the presence of cliffs or of embayments so readily provides? The only answer is that he saw no necessity of looking for an impartial test; in other words, that his method of scientific investigation was not the same as the one here adopted. He seems to have been satisfied because his theory explained the things that it was invented to explain; he asked nothing more of it! Not only so, some of his readers also were satisfied, and spoke of his essay with high praise: hence we must suppose that they too were ready to accept a theory that merely explained the things that it was invented to explain, instead of suspending their judgment until the theory should be shown competent to explain also certain other things that it had not been invented to explain. It is cases of this kind, which give warrant to the statement made on an earlier page, that in many published studies of the coral-reef problem, "the methods employed have been incomplete, illogical and untrustworthy, and the results reached are therefore unconvincing."

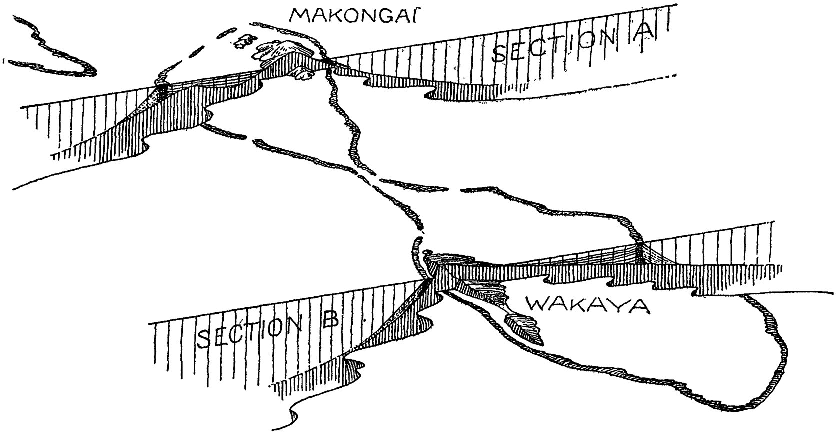

FIG. 10. BLOCK DIAGRAM OF WAKAYA, a tilted and slightly dissected fault block, and MAKONGAI, a maturely dissected volcanic mass, in the Fiji group; the two islands are enclosed in a double-looped barrier reef. Vertical sections, *A* and *B*, are drawn through the islands to show the inferred submarine relations of island to reef.

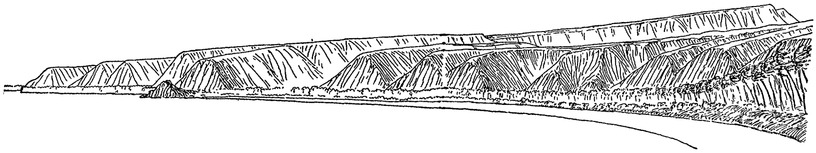

FIG. 11. SKETCH OF CLIFFED SPUR ENDS, northeast coast of the submaturely dissected volcanic cone of Tahiti, Society islands.

Exceptional Examples.—But has the veneering hypothesis really no independent support? Yes, in two exceptional examples the central islands of barrier reefs are cliffed around part of their margin: one is

Tahiti, Fig. 11, but there, as above intimated, it may be shown that the spur-end cliffs as well as the inter-spur valleys were cut when the island stood higher than now, and that since then the island has been submerged, for its valleys between the truncated spur ends are occupied either by arms of the sea or, more generally, by the heads of delta plains, as in Fig. 12. The other example is New Caledonia, which is strongly cliffed at its southeastern end and along part of the northeastern side; but as at Tahiti, these cliffs, as well as the numerous valleys of this long island, were cut when the island stood higher, and the same submergence that has embayed the valleys has half-drowned the cliffs. Hence, the two best examples of becliffed islands, though peculiar in possessing cliffs, are not peculiar also in having stood still, for both have suffered submergence. These islands are truly of great interest and merit special study; but they are as truly exceptions in the long list of reef-encircled islands, in which the spurs that separate the embayments as a rule taper down gradually, and dip below the sea with nothing more than little nips or low bluffs cut by the lagoon waves close to present sea-level. The great majority of volcanic islands are not cliffed at all in the way the hypothesis of veneering barrier reefs and atolls demands, and for them the hypothesis must be rejected completely. Yet this hypothesis was presented with so convinced an emphasis by its above-quoted advocate, that an eminent geologist thereupon wrote:

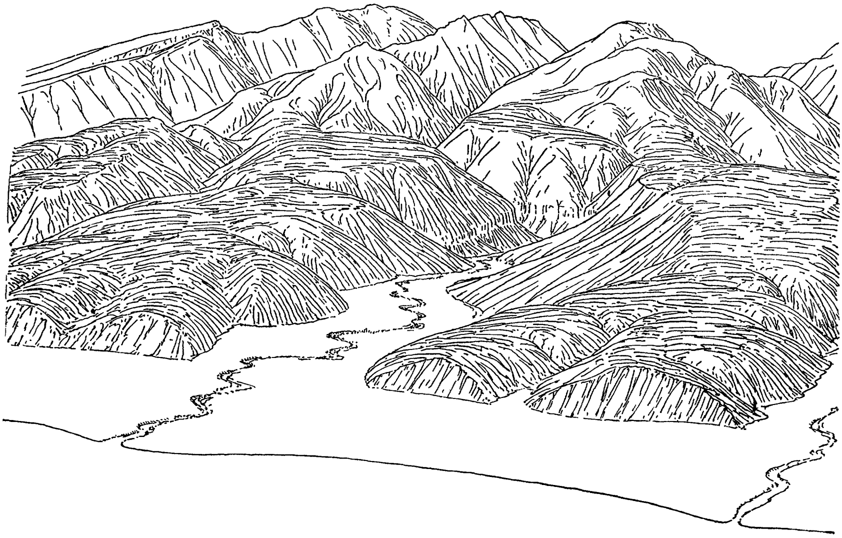

FIG. 12. BIRD'S-EYE DIAGRAM OF NORTHERN COAST, TAHITI, showing cliffed spur ends, separated by delta-filled embayments and prograded by a half-mile alluvial plain. The plain is for the most part covered with palm trees. Papeete, the capitol, lies on the plain to the left of the diagram.

> I have read Dr. ——————'s paper with great interest, and am of opinion that he has made out a very strong case indeed against the theory of

> coral island formation advanced by Mr. Darwin. . . . The famous Darwinian theory of coral reefs can no longer be said to hold the field.

Another critic said that, if the facts and arguments here adduced had been known to Darwin,

> the great naturalist would have accepted the explanation of the phenomena now formulated, and would have given up his ingenious theory of gradual elevations and subsidences of the sea bottom.

A third critic wrote, in view of the still-stand and the veneering theories:

> It is somewhat surprising that, in the discussion which has lately [1883–1888] been carried on in the English reviews . . . regarding the new theory of coral reefs, no one should have dwelt upon the fact, that, with the exception of Dana, Jukes, and others who published their results on coral reefs soon after Darwin's theory took the scientific world by storm, not a single recent investigator of coral reefs has been able to accept this explanation as applicable to the special district which he has examined.

A fourth said:

> A singular feature of these papers [at the British Association meeting, 1888] is the almost complete unanimity with which those authors, who have themselves practical experience of coral reefs, reject the subsidence theory as inadequate, or unnecessary.

Thus it would appear that Darwin's theory was well nigh abandoned. But none of these critics asked: Are the central islands of barrier reefs cliffed or delta-fronted, as they should be according to other hypotheses? All of which goes to show that the method of scientific investigation applicable to coral reefs is far from having been standardized; for as soon as the consequences of the hypothesis of veneering reefs are explicitly deduced and frankly confronted with the appropriate facts, the hypothesis must necessarily be given up by any independent investigator who demands that such confrontation shall be successful before he gives faith to the hypothesis that brings it forth. Yet this theory was set forth for the Great Barrier reef of Australia with such vigor by a zoological expert that another zoological expert declared the theory of subsidence to be "absolutely excluded" as an explanation for that greatest of all reefs; although the not cliffed but deeply embayed coast of Queensland presents abundant and convincing evidence that strong subsidence has taken place, as was pointed out by Penck in 1896, as has later been shown by Andrews and other Australian observers in 1902, and following years, and as I had occasion of seeing for myself along a stretch of several hundred miles in 1914.

(To be continued)